The Effects of Prescribed Fire on Roosting Habitat of the Endangered Indiana Bat, *Myotis sodalis*

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Abstract

This study investigated the compatibility of fuel treatments and fire management in the southern Appalachian Mountains with the conservation of the federally endangered Indiana bat (*Myotis sodalis*). Our objectives were: 1) measure snag population dynamics in prescribed fire treatment and control sites at multiple landscape positions, 2) measure the availability of snags suitable for Indiana bats in multiple landscape positions in stands with a range of prescribed fire histories, and 3) identify the multi-scale characteristics of day roost sites used by Indiana bats in pine-hardwood stands in landscapes managed with prescribed fire. The study was conducted in 3 areas in the southern Appalachian Mountains: 1) Cherokee National Forest (CNF) in Tennessee, 2) Nantahala National Forest (NNF) in North Carolina, and 3) Great Smoky Mountains National Park (GSM) in North Carolina and Tennessee. We established 21 treatment (6 CNF, 6 GSM, and 9 NNF) plots in 8 proposed burn units and 18 control (6 CNF, 3 GSM, and 9 NNF) plots to assess the effects of prescribed fire on existing snags and creation of new snags. Treatment and control plots were in mixed pine-hardwood units that experienced fire once or not at all in the past 10 years. To test the effects of fire history and landscape position on roost availability, we surveyed 2 transects of each unique combination of burn history (unburned, burned once in past 10 years, or burned twice in past 10 years) and slope position (lower, middle, or upper) in stands with a mature pine component in each study area (18 transects per study area, for a total of 54 transects). These plots were measured from May-November, 2010-2012. From 2010–2012, we conducted a radio telemetry study on Indiana bats from mid-May to early August each year.

We determined that the effects of prescribed fire on snags varied with slope position, fire intensity, and snag characteristics. Our data suggest that large snags are lost and small snags are gained in plots that experience fire, particularly when the fires are very hot (>100 °C). With one exception, middle and upper slope plots were hottest parts of burns, which is evidence that slope position affects snag fates. We found no evidence that snag availability varied with fire history, as yellow and white pine snags were found fairly evenly in plots burned twice, once, or not at all in the past 10 years. However, there were significantly more pine snags (especially yellow pine) on middle and upper slopes, suggesting that landscape position affects roost availability for Indiana bats.

We modelled Indiana bat roost selection at the landscape scale using MAXENT and found that Indiana bats selected roosts in areas where yellow pines are most common – south facing, middle elevation slopes. When we considered factors at multiple spatial scales in case-control models, we found that tree and plot-level factors were most important in roost selection. Bats were more likely to use tall yellow pine snags surrounded by a greater density of dead trees. Collectively, the data from this study show that prescribed fire can play an important role in management for Indiana bats in the southern Appalachians. Repeated use of prescribed fire may be important for restoring yellow pines, but first entry burns in spring can cause significant losses to large snags on middle and upper slopes, which is where bats are most often found roosting.

Background and Purpose

This study investigated the compatibility of fuel treatments and fire management in the southern Appalachian Mountains with the conservation of the federally endangered Indiana bat (*Myotis sodalis*). Because it was a landscape-scale study, we expect our results to be used by land managers throughout the southern portion of the Indiana bat's range.

The Indiana bat is an insectivorous bat distributed throughout much of the eastern U.S. (Fig. 1; Gardner and Cook 2002). Despite federal protection and the initiation of recovery measures, the population declined 57% from 1965 to 2000 (Clawson 2002) probably mainly due to human disturbance at hibernacula, habitat changes, and other anthropogenic factors. However, the epidemic white-nose syndrome (WNS) now poses an additional threat to the Indiana bat. WNS is found throughout most of the Indiana bat's range (Turner et al. 2011) and Indiana bat populations are projected to experience severe declines or extirpation throughout their range as a result of WNS (Thogmartin et al. 2013). Conserving healthy summer populations of Indiana bats may be critical to the overall survival of the species.

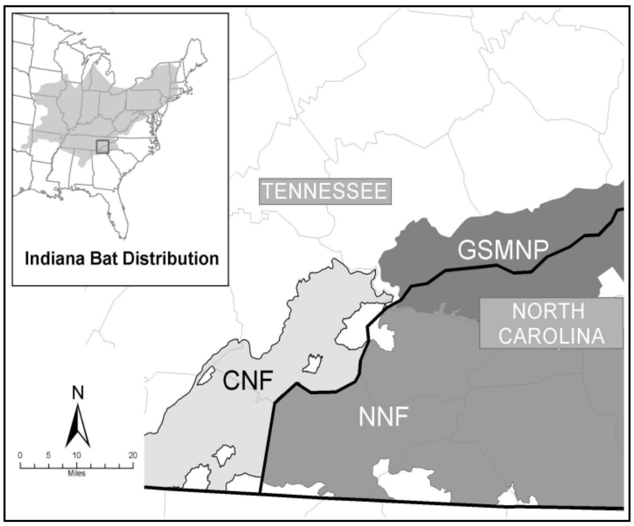


Figure 1. Distribution of the Indiana bat (inset) and study areas in eastern Tennessee and western North Carolina.

During summer, female Indiana bats form maternity colonies, give birth, and raise their young in cavities or crevices in large dead or damaged trees with open canopies. Primary maternity roosts (Callahan et al. 1997) in the southern Appalachians are often under the sloughing bark of dead southern yellow pines, mainly shortleaf pine (*P. echinata*), with >50% bark but, in a study by Britzke et al. (2003), roosts were unsuitable 1 year after they were found. The majority of roosts are on mid and upper slopes in mixed pine-hardwood stands, but some non-pine roosts have been found near streams.

In the southern Appalachians, fire has become an important tool for the restoration of oak (*Quercus*) and yellow pine (*Pinus* subgenus *Diploxylon*) forests (Elliott et al. 1999, Waldrop and Brose 1999). On federal lands in this region, resource managers implement landscape-scale (500–4000 ac) dormant season burns using burn protocols designed to mimic natural lightning-set fires on ridgetops. Lafon et al. (2007) predicted that in the absence of regular fire, yellow pines would disappear from south- and west-facing slopes, and ultimately would be replaced by hardwoods, even on ridgetops.

Fire may be necessary for the persistence of yellow pine forests in this region (Lafon et al. 2007) and, if pines are important roost types, fire could be a critical management tool for sustaining Indiana bat roosting habitat. In addition, open canopy conditions created by frequent burning could be ideal for Indiana bats, as females in the midwestern U.S. select trees with high solar exposure (Kurta et al. 2002, Carter and Feldhammer 2005). Snags are critical habitat for Indiana bats (USFWS 2007) and, currently, yellow pine snags are abundant in the southern Appalachians due to a massive pine beetle outbreak that occurred in the late 1990s and early

2000s. However, one of the primary justifications for this study was that little is known about how prescribed fire for habitat restoration and fuels management affects existing snags and whether fire can create a sufficient number of snags to replace those that are destroyed.

There were three primary objectives for this study. First, we aimed to measure snag population dynamics in prescribed fire treatment and control sites at multiple landscape positions. We tested the hypothesis that populations of large snags are affected by fire, and that responses would vary with slope position, fire intensity, and snag characteristics. Second, we aimed to measure the availability of snags suitable for Indiana bats in multiple landscape positions in stands with a range of prescribed fire histories. We tested the hypothesis that roost availability varies with landscape position and fire history. Finally, we sought to identify the multi-scale characteristics of day roost sites used by Indiana bats in pine-hardwood stands in landscapes managed with prescribed fire. We tested the hypothesis that roost habitat selection is non-random with respect to fire history, and tree, plot, stand, and landscape characteristics.

Methods and Location

Study Area

The study was conducted in 3 areas in the southern Appalachian Mountains: 1) CNF (Cherokee National Forest, Polk and Monroe counties, TN), 2) NNF (Nantahala National Forest, Cherokee, Graham, and Swain counties, NC), and 3) GSM (Great Smoky Mountains National Park, Swain County, NC; Blount and Sevier counties, TN). The primary natural community types used by bats were pine-oak heath, Carolina hemlock forest, white pine forest, low mountain pine-oak forest, and southern mountain xeric pine-oak woodland (Schafale 2012). Various oak and cove forest types also occurred in our study area. The majority of the study area was forested habitat (> 90%), mainly mid-successional forest (41–80 years old), but also included young and old-growth forests (Franzreb 2005). Elevation ranged from 250–2025 meters above sea level.

Objective 1. Effects of prescribed fire on snag population dynamics

Beginning in Fall 2009, we established 21 treatment (6 CNF, 6 GSM, and 9 NNF) in 8 proposed burn units (Table 1) and 18 control (6 CNF, 3 GSM, and 9 NNF) plots to assess the effects of prescribed fire on existing snags and creation of new snags; we also established plots in 1 temperature-only unit on NNF. Treatment and control plots were in mixed pine-hardwood units that experienced fire once or not at all in the past 10 years. Controls matched treatment plots for prior burn frequency and were not burned during this study. In each burn unit, our goal was to establish plots on upper, mid, and lower slopes (1 each), focusing on habitats likely to contain suitable roosts for Indiana bats. Slope classes were defined as follows: upper was on a ridgetop and relatively flat, middle was a side slope and relatively steep, and lower included a streambed and was relatively flat.

In establishing plots, we targeted areas of 1 slope class containing~40 snags. In some instances it was not possible to find 40 snags in one area; in these cases, fewer snags were marked. For each snag, we recorded species (if possible), height, dbh, cause of mortality (if possible), and several decay status metrics. For decay, we measured overall decay status (1–4, modified from Ormsbee 1996; Table 2), branch state (1–5, by size and number), bark tightness (1–3), percent remaining bark, and surface wood hardness (1–4, Bagne et al. 2008). For live trees, we recorded species, height, and dbh; if a live tree died then we converted it to a snag in our database. Trees were marked with numbered tags (brass in treatments and aluminum in controls) and we recorded coordinates for each tree with a Trimble GEO-XT (Sunnyvale, CA) GPS. During each survey, we also tallied all of the small snags (9.2–18.3 cm dbh) within the bounds of the plot, as delineated by the outermost tagged trees.

Table 1. Units where treatment plots were established and status of burns. Data collected includes fates of live and dead trees marked prior to the burn (tree fates) and temperatures at the base of marked snags within plots (temps). We were not able to collect both types of data in every burn.

Agency	Unit	Status	Burn Date	Data Collected
NNF	Panther Top	Burned	20 Mar 2010	tree fates; temps
NNF	Yellow Creek	Burned	2 April 2010 & Fall 2012	tree fates; temps
NNF	Elbow Creek	Burned	22 Mar 2011	tree fates; temps
NNF	Chambers Creek*	Burned	20 Mar 2012	temps
CNF	Hurricane Branch	Burned	20 Mar 2010	tree fates; temps
CNF	Whigg	Burned	5 Mar 2011 & 11 Mar 2012	tree fates; temps
GSM	Lynn Hollow	Burned	April 2014	in progress: tree fates
GSM	Hatcher Mountain	Not burned	-	-

*Not considered treatment plots

Table 2. Definitions of 4 decay stages assigned to snags encountered in burn/control plots and snag availability plots, as well as to roosts and random trees.

	Overall Decay Status			
	1	2	3	4
Branches	80-100	few-no branches	limb stubs to none	none
Bark Tightness	80-100	30-80% remaining	has most of height and ≤30% bark, or has <50% of height and ≥80% bark	<80% bark
Height	full-broken top	broken top	broken top to <50% height	<50% of height

The Hurricane Branch and Panther Top units burned in March 2010. Elbow Creek, a burn unit that was not part of our original study plan, burned in March 2011. The Whigg unit burned in April 2011, and was successfully burned again in March 2012 (the second burn was unplanned for this study). Yellow Creek was burned successfully in April 2010. In Fall 2012, the Yellow Creek unit was lit by an arsonist. To control the spread of the arson fire, USFS fire personnel conducted a prescribed burn within the boundaries of the original Yellow Creek burn. Hence, this unit was burned twice during this study, which was unplanned.

The Hatcher Mountain burn did not occur because the unit was decimated by an F4 tornado in April 2011; further, we never established control plots for this burn. Though we expected the Lynn Hollow unit to burn in late March 2012, weather conditions were not ideal for smoke dispersion and the burn was cancelled. Concerns about effects of spring fires on Indiana bats, which hibernate in GSM, have led to restrictions on burn windows in early April; this concern, plus limited funding, meant that the Park was not able to burn this unit during our study. The Lynn Hollow burn did take place in April 2014.

In Spring 2011, we marked 6 randomly selected snags in 2 new plots (1 upper, 1 mid) in the Chambers Creek burn unit, which was new to the study. Our goal was merely to gather more temperature data for snags during a burn, not to track the long term fate of trees in the unit.

We measured temperatures in the Panther Top, Hurricane Branch, Whigg, Yellow Creek, and Chambers Creek burns. In each burn, we buried 1 HOBO data logger (model U12-014) and 12" Type K Thermocouple (Onset Computers, Bourne, MA) in each of the 4 cardinal directions ~0.5 m from the trunk of 6 randomly selected marked snags in each plot, such that 24 HOBOs were installed in each of 3 plots for the duration of each fire. In the Chambers Creek burn, we only marked and measured 12 snags total, 6 in an upper and 6 in a midslope plot (no lower plot). HOBOs were either preset to turn on just before the start of the burn or we activated them in the field before burying them the day of the burn.

All plots established in prior seasons were re-visited each summer or fall after they were burned, including 2013, with the exception of the Hatcher Mountain burn. During visits, we took measurements on all snags and we reassessed the status of each marked live tree. As of August 2014, we had not quite completed the re-measuring of the Lynn Hollow burn plots.

Objective 2. Landscape-scale roost tree availability

To test the effects of fire history and landscape position on roost availability, we surveyed 2 transects of each unique combination of burn history (unburned, burned once in past 10 years, or burned twice in past 10 years) and slope position (lower, middle, or upper) in stands with a mature pine component in each study area (18 transects per study area, for a total of 54 transects). These plots were measured from May-November, 2010-2012. For each snag inside a randomly placed 100 m X 40 m rectangle that we created in a GIS and displayed on a Trimble GEO-XT, we recorded coordinates and measured species (if possible), height, dbh, cause of mortality (if possible), and several decay status metrics. For decay, we measured overall decay status (1–4, modified from Ormsbee 1996; Table 2), branch state (1–5, by size and number), bark tightness (1–3), percent remaining bark, and surface wood hardness (1–4, Bagne et al. 2008). We also tallied the presence of live trees by species and dbh classes (18.4–28.3 cm, 28.4–38.3 cm, and so on) inside this rectangle.

Objective 3. Indiana bat roost tree selection in relation to fire history, and stand and landscape characteristics

From 2010–2012, we conducted a radio telemetry study on Indiana bats, working from mid-May to early August each year. We included data from earlier work in 2008-2009 in our models. We used mist nets to capture bats over road/stream corridors. Captured bats were identified, sexed, aged, measured (forearm length and weight), and banded with a unique aluminum forearm band. We attached 0.32–0.42 g radio transmitters (Holohil Systems, Ltd., Canada) and bats were released at the point of capture. We used 3- and 5-element Yagi antennae and a receiver (Telonics, Mesa, AZ) to locate day roosts for each bat, and emergence counts were conducted at each roost, as feasible. For selected roosts, we deployed a datalogging receiver (Lotek Wireless, SRX-DL2) to record body temperature of individual bats at roosts throughout the day; this receiver also scanned for all programmed frequencies within a small area around each tree.

For most roost trees, we identified a random snag with visible roost potential at a random point on the landscape <4 km from the capture site (location contingent on roost proximity to capture site). At each focal (roost or random) tree we recorded species, dbh, height, and distance to and height of the closest tree ≥10 cm dbh and the closest tree the same height or taller. We measured all trees ≥10 cm dbh to calculate live and dead tree basal areas in a 0.1 ha plot around each focal tree. For live trees, we recorded species, dbh, height relative to focal tree, and roost potential, and for dead trees we recorded species, dbh, and overall decay stage (Table 2). We tallied all saplings ≤8.9 m from the focal tree according to 5 diameter classes. For each quarter plot, percent canopy closure was estimated to the nearest 25%. Focal tree coordinates were recorded to facilitate GIS analyses on landscape-scale roost habitat selection.

We took 2 approaches to analyzing roost habitat selection: 1) a landscape-scale model using the presence-only program MaxEnt (part of M.S. thesis by graduate student Kristina Hammond) and 2) a case-control logit model pairing roost trees with random trees. For the 26 candidate landscape-scale models, predictors were topographic variables, forest type, distances to particular features (e.g., roads), and unique landform variables such as ridge curvature. Only roosts that fell on public (national forest or national park) lands were included, as we had landscape-scale vegetation layers only for those properties. For the 15 candidate case-control models, we included variables related to focal tree type and size, clutter, solar exposure, roost switching potential, proximity to foraging areas, and landscape position. Trees used in this analysis were roosts and random trees for which we collected vegetation data in 0.1 ha plots surrounding the focal tree. In both analyses, we used an information theoretic approach to identify the best model(s) (Burnham and Anderson 2002).

Key Findings

Objective 1. Effects of prescribed fire on snag population dynamics

None of the 18 control plots were burned during this study. Prescribed fire was not conducted in 3 of the 21 burn plots we established due to a tornado (Hatcher Mountain) and another 3 plots (Lynn Hollow) due to adverse conditions/planning issues that kept managers from implementing the burn during the study period. For 3 units, fire did not reach every plot (Figure 2). Lower and north facing slopes did not always burn, even when other parts of the burn unit did.

We successfully collected temperature data in 10 plots that experienced fire within 5 burn units (Figure 2). Mean maximum temperature in burn plots ranged from 51–634 ˚C. Temperatures tended to be highest in midslope and upper plots, with the highest mean maximum temperatures recorded in the midslope plots for the Whigg (634.5 ˚C), Yellow Creek (508.6 ˚C), and Chambers Creek (335.6 ˚C) burns.

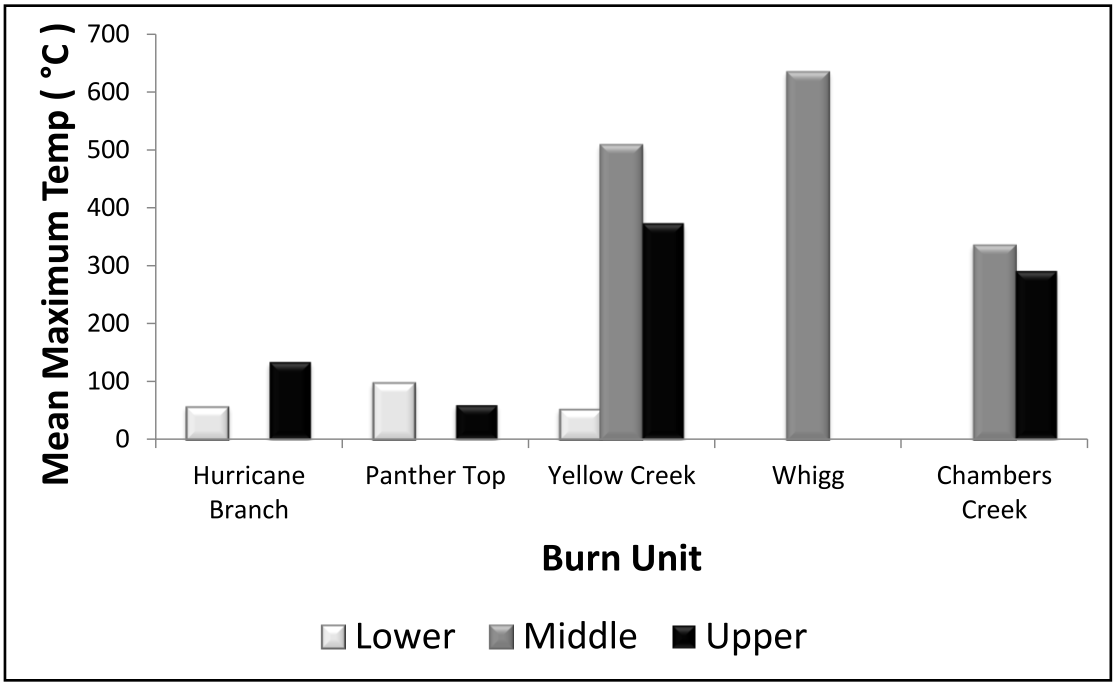


Figure 2. Mean maximum temperatures recorded in 5 burn units in which HOBO dataloggers were deployed. For each burn, we deployed a total of 72 HOBOs; 4 at the base of each of 6 snags in 1 lower, middle, and upper slope plot/burn. Four plots did not burn, so in some cases we do not present fire temperature data. There was no lower plot for the Chambers Creek burn.

Generally, burned units lost more snags than control units (Table 3). Plots with higher fire intensity (Fig. 2) tended to lose more large (≥18.4 cm dbh) snags (Table 3). However, yellow pine snags were lost regardless of fire presence or intensity (Table 3). Overall, plots tended to lose yellow pine and white pine (*P. strobus*) snags (Table 2). Hemlocks (*Tsuga canadensis*) and hardwood snags were lost less often and, in some cases, we saw significant gains in hardwood snags (Table 3). While all plots tended to gain small snags, there was a trend for gaining more small snags in fire plots ($Gain_{FIRE}$=64.7 ± 6.5% snags/plot vs. $Gain_{CONTROL}$=41.5 ± 6.8% snags/plot).

In the Yellow Creek fire, which was one of the more intense burns during the first entry in 2010, 19-28 hardwood snags were created and 17-29 yellow pine snags were lost in both the midslope and upper plots. Although 6-7 hardwood snags were lost in these plots after the arson fire in 2012, there was still a gain of 13-21 hardwood snags in the midslope and upper plots in the last year they were measured (2013).

Table 3. Large (≥18.4 cm dbh) snag fates by plot for 5 burn units that experienced prescribed fire between 2010 and 2012, and for 5 matched control units. Data are presented for 1-2 years pre-burn and the last year each snag cluster was measured (each was measured for 2-4 years post-burn, depending on when the unit burned). Snags are grouped by the major types observed in plots. Percent lost or gained was calculated as [(pre-burn snags – post-burn snags) / pre-burn snags].

					Snags Lost or Gained Pre-burn to Post-burn			
Unit	Plot	Mean Max Temperature (°C)	Pre-burn Measure-ments	Post-burn Measure-ments	Yellow Pines	White Pines	Hemlocks	Hardwoods
Hurricane Branch Burn								
	Upper	133.5	2009	2013	64% lost	100% lost	.	.
	Middle	no fire	2009	2013	28% lost	0 lost	.	13% gain
	Lower	55.3	2009	2013	33% lost	18% lost	100% gain	33% gain
Hurricane Branch Control								
	Upper	no fire	2009	2013	17% lost	100% lost	.	0 lost
	Middle	no fire	2009	2013	13% lost	.	.	33% lost
	Lower	no fire	2010	2013	0 lost	0 lost	.	0 lost
Panther Top Burn								
	Upper	59.5	2009	2013	100% lost	0 lost	.	.
	Middle	no fire	2009	2013	44% lost	8% lost	0 lost	100% lost
	Lower	96.2	2009	2013	53% lost	0 lost	.	200% gain
Panther Top Control								
	Upper	no fire	2010	2013	89% lost	4% lost	.	.
	Middle	no fire	2010	2013	60% lost	67% lost	.	100% gain
	Lower	no fire	2010	2013	29% lost	4% gain	.	100% lost
Yellow Creek Burn								
	Upper	372.7	2009	2013	100% lost	.	.	650% gain
	Middle	508.6	2009	2013	61% lost	100% lost	.	525% gain
	Lower	51.0	2009	2013	.	0 lost	7% gain	50% gain
Yellow Creek Control								
	Upper	no fire	2009	2013	75% lost	50% lost	.	100% lost
	Middle	no fire	2009	2013	50% lost	.	100% gain	100% gain
	Lower	no fire	2009	2013	50% lost	11% gain	8% loss	50% lost
Whigg Burn								
	Upper	no fire	2009	2013	36% lost	.	.	0 lost
	Middle	634.5	2009	2013	70% lost	33% lost	.	75% lost
	Lower	no fire	2009	2013	33% lost	17% gain	140% gain	0 lost
Whigg Control								
	Upper	no fire	2010	2013	28% lost	0 lost	.	20% lost
	Middle	no fire	2010	2013	13% lost	.	.	13% lost
	Lower	no fire	2010	2013	0 lost	3% lost	.	0 lost
Elbow Creek Burn								
	Upper	no temps	2010	2013	63% lost	7% lost	.	50% lost
	Middle	no temps	2010	2013	42% lost	20% lost	.	0 lost
	Lower	no temps	2010	2013	27% lost	29% lost	.	.
Elbow Creek Control								
	Upper	no fire	2010	2013	19% lost	0 lost	.	0 lost
	Middle	no fire	2010	2013	44% lost	3% lost	.	50% gain
	Lower	no fire	2010	2013	14% lost	0 lost	.	.

Objective 2. Landscape-scale roost tree availability

We measured 817 snags in 54 “snag availability” plots on the CNF, NNF, and GSM. Most snags encountered were yellow pines (43%), followed by hardwoods (27%), white pines (17%), and hemlocks (13%). Over 56% of hardwood snags were oaks. There were more snags on upper slopes (18.0 ± 3.0 snags) versus middle (14.5 ± 3.0 snags) and lower (12.9 ± 2.9 snags) slopes.

When considering the effects of fire frequency, hardwood snags were fairly evenly distributed across slope classes and plots that had been burned twice, once, or not at all in the past 10 years. Hemlock snags were found most often in lower plots, regardless of the history of fire frequency. We observed a trend for more white pine snags on upper slopes and in twice burned plots (Fig. 3). More yellow pine snags were observed on middle and upper slopes, but there was no significant effect of fire frequency on yellow pine snag distribution (Fig. 4).

Figure 3. White pine snags (n = 140) observed in 54 snag availability plots burned twice (2X), once (1X), or not at all (0X) in the past 10 years.

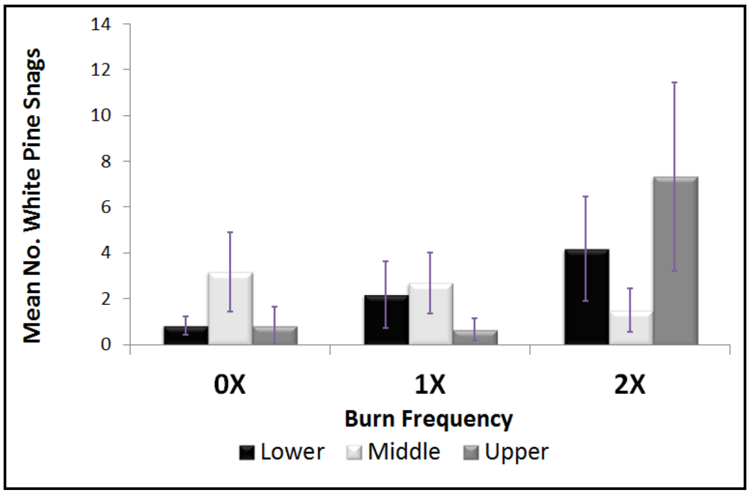
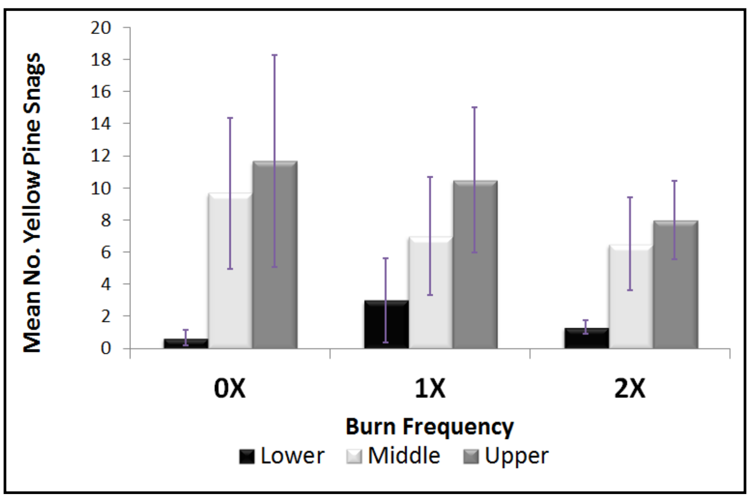
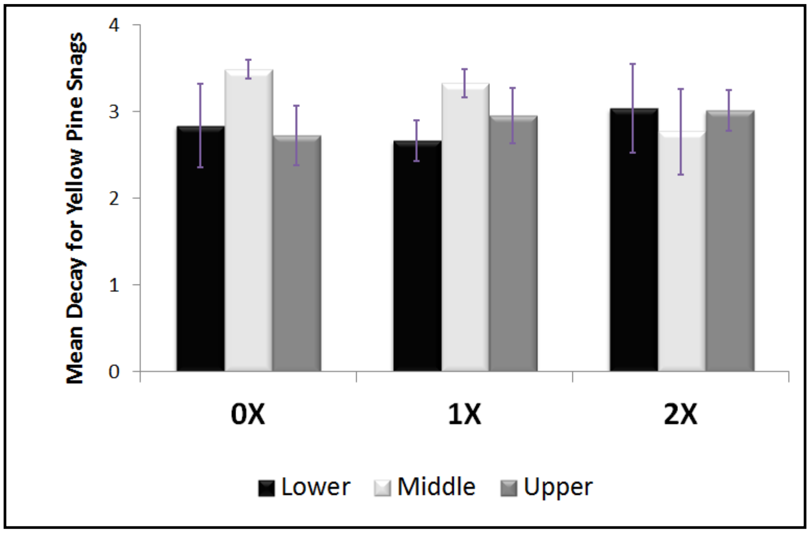


Figure 4. Yellow pine snags (n = 350) observed in 54 snag availability plots burned twice (2X), once (1X), or not at all (0X) in the past 10 years.



Most of the yellow pine snags we encountered were in late stages of decay (decay = 2.9 ± 0.32, Table 2), which indicates a tree with a broken top or <50% of its height, no branches, and little bark remaining. Decay stages of yellow pine snags did not vary with fire frequency (Fig. 5). Hemlocks and white pines were typically less decayed (1.7–2.7) than yellow pines.

Figure 5. Mean decay stage for 350 yellow pine snags measured in plots burned twice (2X), once (1X), or not at all (0X) in at least 10 years. See Table 2 for decay class descriptions.



Objective 3. Indiana bat roost tree selection in relation to fire history, and stand and landscape characteristics

From 2008–2012, we collected quantitative data on 95 Indiana bat roosts in our study area. This includes roosts used by adult females, adult males, and juveniles. Bats typically roosted under the sloughing bark of dead trees. Roosts were primarily large diameter yellow pine (75% of roosts) or white pine snags, of moderate height, and with low canopy closure. These snags were ephemeral and only suitable for 1–2 years before losing all bark or falling to the ground. Decay levels averaged 2.38 ± 0.07 (Table 2). During the study, only 1 roost was used in 2 consecutive years; we noted fewer bats using this roost during exit counts in the second year. We observed that roosts were generally on south facing ridges, often on the upper third of the ridge but generally not at the very top.

Seventy-six roosts used by 48 adult females or juveniles were used as inputs in landscape scale models for Indiana bat roost selection in the MaxEnt program. Pine 2 and Pine 1 were the only models with $\Delta AIC_c < 2$; both accounted for >0.99 of the AICc weights and, therefore, there was a > 99% chance that one of them was the best approximating model for the data and candidate models we tested (Table 4). Forest type, elevation, aspect north/south, and distance to ridge were important predictors in Pine 2 and Pine 1 (Table 5). The composite best models predicted that suitable roost habitat was on the upper portion of south facing slopes in forests with a conifer component, at elevations of 260–700 meters. The final raster (Fig. 6) shows predicted areas of suitable (9% of study area) and optimal (1.5% of study area) habitat based on habitat conditions from 2008–2012. Areas of suitable and optimal habitat were located in areas with known roosts, but also in areas where no roosts were located (Fig. 6).

Table 4. Eleven top-ranked models and the two lowest-ranked landscape-scale MaxEnt models for predicting the presence of Indiana bat summer roosting habitat.

Rank[a]	Model	Number of Parameters	AICc Score	ΔAICc	wi
1	Pine 2	5	1732.3	0	0.55
2	Pine 1	2	1732.8	0.44	0.45
3	Topography 2	4	1758.9	26.56	< 0.01
4	Topography 1	6	1759.6	27.31	< 0.01
5	Elevation	1	1762.5	30.15	< 0.01
6	Research bias 1	3	1764.6	32.28	< 0.01
7	Needs 1	2	1764.6	32.29	< 0.01
8	Ridge 2	3	1764.7	32.34	< 0.01
9	Global	10	1765.6	33.33	< 0.01
10	Needs 3	4	1770.8	38.51	< 0.01
11	Forest Type	1	1779.5	47.15	< 0.01
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25	Sun 1	6	1824	91.69	< 0.01
26	Corridor 3	2	1824.7	92.35	< 0.01

Data are based on 76 roosts located on public land from May to August, 2008–2012 in the southern Appalachian Mountains.

[a]Models were ranked based on ΔAICc.

Table 5. Importance values for variables used in 26 candidate landscape-scale MaxEnt models predicting the presence of Indiana bat summer roosting habitat in the southern Appalachian Mountains.

Environmental Variables	Parameter Importance[a]
Elevation	0.99
Forest Type	0.99
Aspect East/West	0.55
Aspect North/South	0.55
Distance to Ridge	0.55
Slope	<0.001
Curvature	<0.001
Distance-to-Major Rds	<0.001
Distance-to-Trails/Minor Rds	<0.001
Distance-to-Water	<0.001

Models are based on occurrence data collected from May to August, 2008–2012.

[a]Importance values for each variable were based on the AICc weights for each model in which a variable was included.

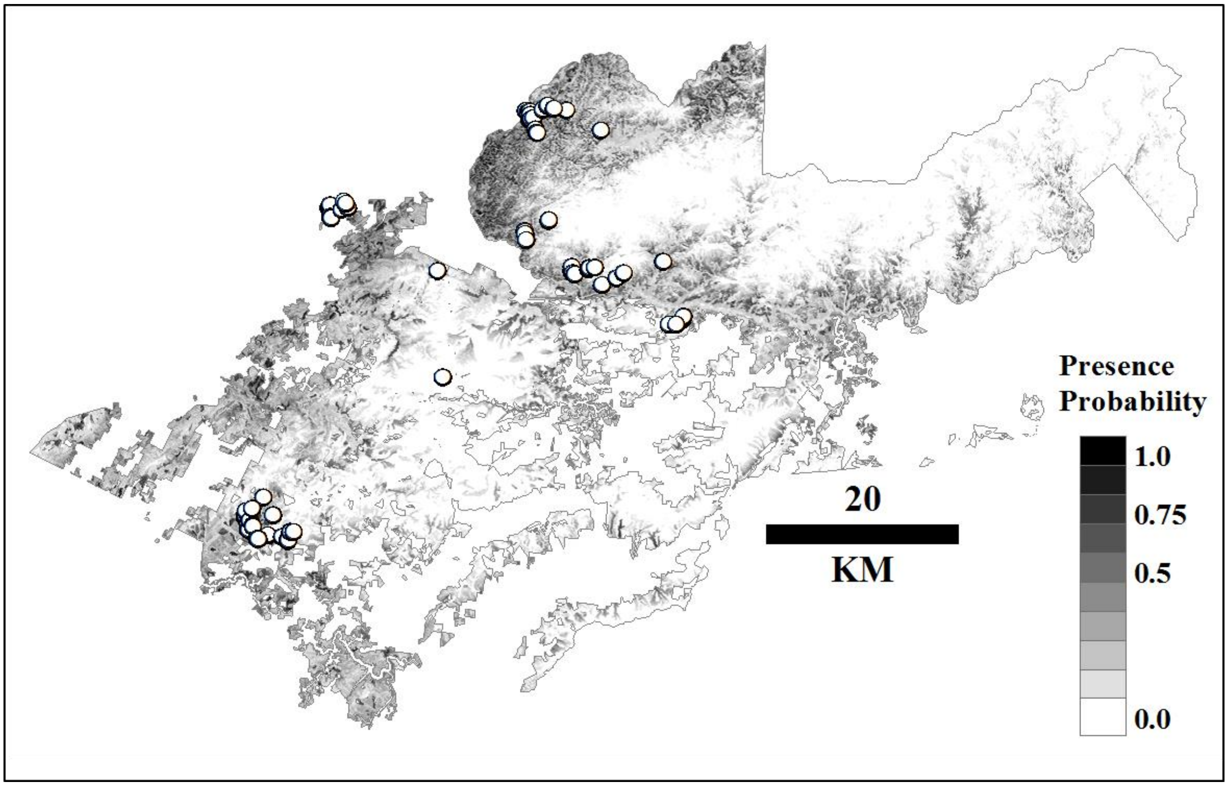

Figure 6. Predicted probability of the presence of summer roosting habitat for female and juvenile Indiana bats in the southern Appalachian Mountains of NC and TN. Probability map is based on the average logistic model from MaxEnt model outputs for 76 roosts (indicated by the white circles) Areas of importance (gray to black areas) are either suitable (≥ 0.5) or optimal (≥ 0.75) summer roosting habitat.

Sixty-nine roosts used by adult females or juveniles were inputs in the case-control logit models to assess Indiana bat roost selection. The best model was a local-scale model, Pine + Solar + Switch (Table 6); there was a 95% probability that this model was the best approximating model for the data tested and no other model was considered important ($\Delta AIC_c < 2$). This best model included the variables yellow pine (1/0), focal tree height, focal tree canopy closure, aspect northsouth, aspect eastwest, distance to ridge, and dead tree count in the 0.1 ha plot. Three of the variables in the Pine + Solar + Switch model were significant. When compared to random focal trees, odds ratios show that bats are more likely to use tall yellow pine snags surrounded by a greater density of dead trees (Table 7). The MaxEnt average model presented in Fig. 6 was tested using the variables aspect + distance to ridge + pine + elevation. This model ranked 11th in the case-control analysis Table 6), suggesting that it was not the best model to explain the differences between roosts and random trees.

Table 6. Fifteen candidate case-control models (including the null model) assessing roost habitat selection by Indiana bats at the tree, plot, stand, and landscape scale in the southern Appalachian Mountains.

Rank[a]	Model	Number of Parameters	AICc Score	ΔAICc	w_i
1	Pine + solar + switch	8	127.64	0	0.95
2	Switch	5	134.31	6.68	0.03
3	Large dead trees	6	135.62	7.98	0.02
4	Solar tree/plot	5	151.99	24.36	<0.01
5	Large trees + solar + switch	8	154.90	27.26	<0.01
6	Midwestern model	6	182.38	54.74	<0.01
7	Mountain riparian	6	188.12	60.48	<0.01
8	Yellow pines	6	190.94	63.3	<0.01
9	Foraging water	3	191.52	63.88	<0.01
10	Null	1	193.33	65.69	<0.01
11	MaxENT avg model	7	194.82	67.18	<0.01
12	Foraging open	5	197.15	69.52	<0.01
13	Low plot clutter	6	198.20	70.56	<0.01
14	Solar/temp landscape	5	199.57	71.94	<0.01
15	Fire adapted stands	7	200.02	72.39	<0.01

Data are based on 69 roosts located from May to August, 2008–2012 in the southern Appalachian Mountains.

[a]Models were ranked based on ΔAICc.

Table 7. Odds ratios and 80% confidence intervals for the 3 important variables in the Pine + Solar + Switch case-control model for Indiana bat roost habitat selection.

Variable	Odds Ratio	80% CL_{LOWER}	80% CL_{UPPER}
Yellow pine (1/0)	7.08	3.09	16.27
Height (m)	1.2	1.12	1.27
Dead tree count (#)	1.24	1.16	1.35

Conclusions

Overall, we determined that yellow pine snags are an important roost type for Indiana bats in the southern Appalachian Mountains and that these ephemeral resources are affected by prescribed fires.

We determined that the effects of prescribed fire on snags varied with slope position, fire intensity, and snag characteristics. Our data suggest that large snags are lost and small snags are gained in plots that experience fire, particularly when the fires are very hot (>100 °C). With one exception, middle and upper slope plots were hottest parts of burns, which is evidence that slope position will affect snag fates. Yellow pine and white pine snags were most common pre-burn, so it was not unexpected that these snags would be lost more often. There were fewer hemlock and hardwood snags pre-burn, but in 1 very hot fire (Yellow Creek) many hardwood snags were created. Thus, snag fates (destroyed or created) appear to vary by tree species.

Most of the Indiana bat roosts found during this study were yellow or white pine snags. The landscape-scale snag availability study showed that even though yellow pine snags are the most common type on the landscape, most of these snags are too decayed to be suitable as roosts. We did not find evidence that snag availability varied with fire history, as yellow and white pine snags were found fairly evenly in plots burned twice, once, or not at all in the past 10 years. However, there were significantly more pine snags (especially yellow pine) on middle and upper slopes, so we do have evidence that landscape position affects roost availability for Indiana bats.

When comparing the data from this study to roost data from other regions, it is apparent that Indiana bats are more selective about the types of roosts they use in our study area versus other regions (e.g., southern Illinois, Carter and Feldhamer 2005) or where contiguous forest cover is lacking (e.g., eastern Michigan, Kurta et al. 2002). The landscape-scale (MaxEnt) modeling approach showed that Indiana bats are selecting roosts in areas where yellow pines are most common – south facing, middle elevation slopes. When we considered factors at multiple spatial scales in case-control models, we found that tree and plot-level factors were most important in roost selection. It is important to recognize that in case-control models both roosts and random trees were located in the same moderate to high suitability portions of the overall landscape and, thus, landscape-scale factors were less likely to outperform tree, plot, and stand-scale factors in multi-scale models. Therefore, it is necessary to consider the results of both approaches when assessing the hypotheses we tested. Combined, these analytical approaches suggest that Indiana bats are responding to a pulsed resource (dead yellow pines) at multiple spatial scales. At the tree level, Indiana bats select for tall, dead trees. At the plot level, they tend to use trees surrounded by other snags. Both modeling approaches revealed that bats are selecting for yellow pine stands, which, at the landscape-scale, tend to occur on middle and upper slopes 260–700 m in elevation. Because yellow pine presence and regeneration is greatly affected by fire frequency (Lafon et al. 2007), we propose that during this study Indiana bat roost habitat selection was non-random with respect to fire history in the southern Appalachians.

Though we did not measure pine regeneration, we noticed that pine seedlings were not common in burned units, even in twice burned areas like Yellow Creek. During our Spring 2013 workshop (see Appendix 4), fire managers noted that more frequent fires would be needed to promote pine regeneration in the stands we surveyed. Most of the burns in this study were first entry fires after a long absence. Pine regeneration may be promoted and rates of destruction of large snags may be diminished if fire frequency is increased.

Collectively, the data from this study show that prescribed fire can play an important role in management for Indiana bats in the southern Appalachians. Repeated use of prescribed fire may be important for restoring yellow pines (but we have no data to this effect), but first entry burns in spring can cause significant losses to large snags on middle and upper slopes, which is where bats are most often found roosting. Managers would be remiss to focus only on yellow pine restoration, however, as Indiana bats have proven to be flexible in terms of types of roosts used, both in this study and across the species' ranges.

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Deliverables

Appendix 1. Deliverables associated with JFSP Project Number 09-1-08-2, PIs O'Keefe and Loeb

Proposed	Delivered	Status
Website to provide up-to-date detailed information on the study.	http://www.srs.fs.usda.gov/uplandhardwood/research-topics/duplicates/bats-fire.html	Complete; Will continue to update website with research results
1½ day workshop for managers & biologists	Held workshop in April 2013; workshop was attended by over 65 people from 13 states	Complete
Preliminary & final results will be presented at regional or national meetings & workshops	23 presentations in 2010-2014	Complete
Publication: Effects of fire on snag population dynamics	2 manuscripts in preparation	In progress
Publication: Roost tree selection and availability in relation to fire	1 M.S. thesis completed, 3 manuscripts in preparation	In progress
Dataset: Locations and attributes of Indiana bat roost trees	Stored at ISU and delivered to US Fish and Wildlife Service in annual reports	Complete
Dataset: Locations and attributes of trees in transects surveyed for objectives 1 & 2	Stored at ISU and USDA Forest Service	Complete
Computer model: Categorical model of snag fates in relation to size class, species, decay state, and fire spread and temperature.	Awaiting final data post-burn from Lynn Hollow burn in Great Smoky Mtns National Park	In progress

Appendix 2. Publications associated with JFSP Project Number 09-1-08-2, PIs O'Keefe and Loeb

Hammond, K.R. 2013. Summer Indiana Bat Ecology in the Southern Appalachians: An Investigation of Thermoregulation Strategies and Landscape Scale Roost Selection. M.Sc. Thesis, Indiana State University. 87 pp.

Hammond, K.R., J.M. O'Keefe, S.C. Loeb, and S.P. Aldrich. *In prep*. A Presence-Only Model of Suitable Habitat for the Endangered Indiana Bat in the Southern Appalachians. Revising from earlier submission to submit to PLoSOne.

Hammond, K.R., J.M. O'Keefe. *In prep*. Influence of extrinsic environmental variables on body temperature of female Indiana bats in summer roosts.

O'Keefe, J.M., S.C. Loeb. *In prep*. Multi-scale Roost Habitat Selection by Indiana Bats in the Southern Appalachian Mountains, USA.

O'Keefe, J.M., S.C. Loeb. *In prep*. Effects of fire frequency and landscape position availability of snags in the southern Appalachian Mountains.

O'Keefe, J.M., S.C. Loeb. *In prep*. Effects of prescribed fire on snag populations in the southern Appalachian Mountains.

Appendix 3. Presentations associated with JFSP Project Number 09-1-08-2, PIs O'Keefe and Loeb

O'Keefe, J.M. and S.C. Loeb. 2010. Effects of prescribed fire on roosting habitat of the endangered Indiana bat, *Myotis sodalis*. Oral presentation, North American Society for Bat Research, Denver, CO.

O'Keefe, J.M., H.L. Stewart, and S.C. Loeb. 2010. Snag population dynamics relative to Indiana bat roost habitat selection in the southern Appalachian mountains. Oral presentation, 20th Colloquium on Conservation of Mammals in the Southeastern United States, Asheville, NC.

O'Keefe, J.M. and S.C. Loeb. 2011. Indiana bat roost tree selection in the southern Appalachian Mountains. Poster presentation, 21st Colloquium on Conservation of Mammals in the Southeastern United States, Louisville, KY.

Loeb, S.C. and J.M. O'Keefe. 2011. Bats and fire: management and mitigation. Oral presentation, Annual Meeting of the Southern Blue Ridge Fire Learning Network, Del Rio, TN.

Hammond, K.R. and J.M O'Keefe. 2011. Comparison of body temperature and movements among reproductive classes of roosting *Myotis sodalis* in the Southern Appalachians. Poster presentation, 41st Meeting of the North American Society for Bat Research, Toronto, Canada.

Clark, S., K. Franzreb, C. Greenberg, T. Keyser, S. Loeb, D. Loftis, H. McNab, J. O'Keefe, C. Schweitzer, M. Spetich.. 2011. Research on effects of prescribed fire in southern ecosystems. Poster presentation, 4th Fire in Eastern Oaks Conference, Springfield, MO.

O'Keefe, J.M., S. Bergeson, K. Hammond, S. Loeb, B. Walters, and J.O. Whitaker, Jr. 2012. Roosting ecology of Indiana bats in forested and fragmented landscapes. Oral presentation, Midwest Fish and Wildlife Conference, 73rd annual meeting, Wichita, KS.

Hammond, K.R., J.M. O'Keefe, S.P. Aldrich, and S.C. Loeb. 2012. Modeling Indiana bat (*Myotis sodalis*) summer roosting habitat in the southern Appalachians. Oral presentation, 66th Annual Conference of Southeastern Fish and Wildlife Agencies, Hot Springs, AR.

O'Keefe, J.M. and S.C. Loeb. 2012. The effects of prescribed fire on roosting habitat of the endangered Indiana bats, *Myotis sodalis*. Oral presentation, 23rd Great Smoky Mountains Science Colloquium, Gatlinburg, TN.

O'Keefe, J.M., S.M. Bergeson, K.R. Hammond, S.C. Loeb, B.L. Walters, J.A. Weber, and J.O. Whitaker. 2012. Roosting ecology of Indiana bats in forested and fragmented landscapes. Oral presentation, 42nd meeting of the North American Society for Bat Research, San Juan, Puerto Rico.

Hammond, K.R., J.M. O'Keefe, and S.C. Loeb. 2012. Movements and roost fidelity by Indiana bats in the soutern Appalachian Mountains. Oral presentation, 22nd Colloquium on Conservation of Mammals in the Southeastern United States, Louisville, MS.

Hammond, K.R. and J.M. O'Keefe. 2013. Indiana bat movements and roost fidelity in the Southern Appalachians. Oral presentation, Prescribed Fire and Indiana Bats Workshop, Fontana Dam, NC.

Hammond, K.R., J.M. O'Keefe, S.P. Aldrich, S.C. Loeb. 2013. Presence only modeling of Indiana bat (*Myotis sodalis*) summer roosting habitat in the southern Appalachian mountains. Oral presentation, Midwestern Bat Working Group, Munice, IN.

Hammond, K.R., J.M. O'Keefe, S.P. Aldrich, and S.C. Loeb. 2013. Presence only modeling of Indiana bat (*Myotis sodalis*) summer roosting habitat in the southern Appalachian mountains. Oral presentation, Prescribed Fire and Indiana Bats, Fontana Dam, NC.

O'Keefe, J.M., S.C. Loeb, and K.R. Hammond. 2013. Indiana bat roost habitat selection in the southern Appalachian Mountains. Oral presentation, 16th International Bat Research Conference and 43rd North American Symposium on Bat Research, San Jose, Costa Rica..

O'Keefe, J.M., S.C. Loeb, and K.R. Hammond. 2013. Indiana Bat roost habitat selection in the southern Appalachian mountains vs. other regions. Oral presentation, Prescribed Fire and Indiana Bats Workshop, Fontana Dam, NC.

Hammond, K.R., J.M. O'Keefe, S.P. Aldrich, and S.C. Loeb. 2013. Presence only modeling of Indiana bat (*Myotis sodalis*) summer roosting habitat in the southern Appalachian mountains. Oral presentation, 18th Annual Southeastern Bat Diversity Network Meeting, Fall Creek Falls, TN.

O'Keefe, J.M. and S.C. Loeb. 2013. Landscape-scale snag availability related to fire history in the Southern Appalachians. Oral presentation, Prescribed Fire and Indiana Bats Workshop, Fontana Damn, NC.

O'Keefe, J.M. and S.C. Loeb. 2013. Snag fates and temperatures in burn and control plots in the Southern Appalachians. Oral presentation, Prescribed Fire and Indiana Bats Workshop, Fontana Damn, NC.

Hammond, K.R., J.M. O'Keefe, S.P. Aldrich, and S.C. Loeb. 2013. Presence only modeling of Indiana bat (*Myotis sodalis*) summer roosting habitat in the southern Appalachian mountains. Oral presentation, The Wildlife Society, Milwaukee, WI.

O'Keefe, J.M. and S. C. Loeb. 2014. Snag decay and roost selection by Indiana bats in the southern Appalachian Mountains. Invited presentation, Mammoth Cave Bats and Fire Workshop, Mammoth Cave, KY.

O'Keefe, J.M., K.R. Hammond, S.C. Loeb, and S.P. Aldrich. 2014. Indiana bat roost habitat selection in the southern Appalachian Mountains. Oral presentation, 25th Great Smoky Mountains Science Colloquium, Gatlinburg, TN.

O'Keefe, J.M. and S.C. Loab. 2014. Indiana bat roost habitat selection in the southern Appalachian Mountains. Oral presentation, 19th Annual Meeting of the Southeaster Bat Diversity Network and 24th Colloquium on Conservation of Mammals in the Southeastern U.S., Nacogdoches, TX.

Appendix 4. Workshop Summary for JFSP Project Number 09-1-08-2, PIs O’Keefe and Loeb

In April 2013 we held a workshop to present our study results to managers and wildlife biologists throughout the region. The workshop was attended by over 65 people from 13 states representing numerous state and federal agencies, non-governmental organizations, and private consultants. Presentations covered results of our research on tree, stand, and landscape factors associated with Indiana bat roost site selection in the southern Appalachians, movement patterns of Indiana bats in the southern Appalachians, snag availability in relation to fire history, and snag fates in response to fire presence and temperature. Additional presenters discussed the potential effects of climate change on Indiana bats and the consequences for long-term habitat management in the southern Appalachians, results of studies conducted in Kentucky on the effects of prescribed fire on bat activity and insect abundance, history of fire in the southern Appalachians, the difficulties of conducting prescribed fire in the southern Appalachians from a manager’s perspective, and federal guidelines and regulations regarding conservation and management of Indiana bats. Presentations were followed by a group discussion of the pivotal concerns and research questions regarding implementing prescribed fire in the southern Appalachians. A field trip was held on the second day of the workshop during which participants had the opportunity to see several Indiana bat roost trees and learn more about the tree, stand, and landscape features selected by Indiana bats for roosting in the southern Appalachians. We also visited a Yellow Creek prescribed fire and control plot where the fates of snags have been followed for several years.